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AIR POLLUTION EFFECTS ON CATASTROPHIC FAILURE OF METALS

NATIONAL ENVIRONMENTAL RESEARCH CENTER

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Air pollutants contribute to the catastrophic failure of metal structures through the mechnaisms of stress-corrosion cracking, corrosion fatigue, and hydrogen embrittlement. The "Silver Bridge" catastrophe, LORAN tower parts failures, aircraft parts failures resulting in accidents, and communications equipment failures are examples cited that were related to air pollution. An economic analysis of these failures indicated that accompanying injury and loss of life is an annual economic loss to the nation of from $50 million to $100 million.

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SECTION I
CONCLUSIONS

The probable contribution of air pollution to the catastrophic failure of metal structures is a significant problem. Cited examples of failures and an economic analysis based on those failures indicates that injury and loss of life accompany between $50 million and $100 million annually in economic losses for the nation.

Although there is strong evidence that the effect exists, there has been no research to determine relationships between levels of particular pollutants and the occurrance of catastrophic failure of metals.

SECTION II

RECOMMENDATIONS

Both laboratory controlled environment studies and field studies should be initiated to determine relationships between particular pollutant levels and selected alloy systems. The objectives of these studies should be:

(1) To determine if threshold levels of particular pollutants exist below which no failures to a general class of alloys will occur, and.

(2) To determine direct and synergistic effects of pollutants on the rates of failure of alloy systems.

SECTION III
INTRODUCTION

Catastrophic failure of metal structures such as bridges, towers and aircraft components has become a side effect of technological advancement. The development of high strength alloys and the use of those alloys at stress levels based on the same relative design criteria previously used for lower strength materials has contributed to this problem. Another possible contributing factor has been the degrading change in the environment to which these alloys are exposed.

Because such failures often result in the loss of life as well as economic losses, and air pollutants may be a contributing factor, a study was conducted to assess the magnitude of the problem as it relates to air pollution.

This report is the result of that study and is organized in the following manner:

(1) A brief review of definitions and materials associated with stress-corrosion cracking, corrosion-fatigue, and hydrogen embrittlement is given for background information.
(2) Problem areas associated with these failure mechanisms are discussed and examples are cited and,
(3) An economic analysis of the air pollution contribution to this problem is performed based on this information.

SECTION IV

BACKGROUND REVIEW

GENERAL

The spontaneous failure of a metallic structure, a bolt, a cable, or an aircraft landing gear strut can result in a serious or fatal accident. The catastrophe is usually followed by litigations and investigations which eventually cost the public and the nation large sums of money.

A spontaneous failure can be defined as a metallic fracture which gives no visual indication of impending failure such as a telltale corrosive area or an area where the cross section is noticeably reduced by general corrosion.

This survey is concerned with the catastrophic (spontaneous) failure of metals associated with environmental corrosion.

There are three types of catastrophic failure of metals that are associated with environmental corrosion. They are: (1) stress-corrosion cracking, (2) corrosion fatigue, and (3) hydrogen embrittlement.

STRESS-CORROSION CRACKING

It is interesting to note that of the many definitions of stress corrosion cracking, there is not one that has been universally accepted. The following quotation, however, probably represents a good consensus of opinion.

"A rather broad definition of stress corrosion cracking states that it is a form of localized failure which is more severe under the combined action of stress and corrosion than would be expected from the sum of the individual effects of stress and corrosion acting alone. It is characterized by a brittle-type fracture in an otherwise ductile material. The surface direction of the cracks is normal to the tensile direction."[1]

Stress cracking is frequently observed in metals which retain their original bright metallic surface without any outside indication of the corrosion products formed in the cracks.

The environment has a direct effect on stress-corrosion cracking. There are no reported incidents of stress-corrosion cracking in the absence of some corrosive medium.

The principal factors involved in stress-corrosion cracking are stress, environment, time and metallurgical structure of the alloy. These factors interact, one accelerating the action of another, and their relative importance varies. Copson[2] has presented a good summary of these factors.

"If stress-corrosion cracking is to occur, there must be tensile stresses at the surfaces. The stress may be internal or applied. Examples of internal stresses are those produced by nonuniform deformation during cold working, by unequal cooling from high temperature, and by internal structural rearrangements involving volume changes. Stresses induced when a piece is deformed, those produced by press and shrink fits, and near welds, rivets and bolts may be classed as internal stresses.

The actual stress may vary greatly from point to point within the metal, and in some locations be much higher than the average value calculated as

load divided by area. Generally, tensile stresses in the neighborhood of the yield strength are necessary to promote stress-corrosion cracking; but failures have occurred at much lower stress. At these stress levels, a great deal of corrosive attack would be needed to produce failure, if it were not for an interaction between stress and corrosion.

One of the curious aspects of stress corrosion cracking is the wide difference in time required for failure, which varies from a matter of minutes to many years. A long time may be required before corrosion proceeds to the extent that it begins to be accelerated by the tensile stresses present. The more severe the corrosive conditions and the higher the initial stress, the sooner this will happen. With some alloys there is an incubation period during which structural changes such as precipitation are occuring. Thus, aluminum-magnesium alloys (over 6% magnesium) immediately after heat treatment, may not show susceptibility to cracking in accelerated lab tests, but after aging at room temperature for six months, they may stress-corrosion crack rapidly in the same test.....

Perhaps the best known example of stress-corrosion cracking is the season cracking of brass. Exposure to moist ammoniacal atmospheres is particularly drastic in producing cracking, but exposures as mild as the outdoor atmosphere may produce it in time. Instances are on record where brass cracked spontaneously in indoor atmospheres. Ammonia and compounds of ammonia are believed to be the potent agencies, but moisture and oxygen are necessary, and carbon dioxide may have a contributing effect, The mechanism of the cracking is not completely understood, although it has been established that electrochemical factors are involved."[2]

Unfortunately, there is no theory as yet which allows reliable prediction of the occurrance of stress-corrosion cracking. Environments in which stress-corrosion cracking has been observed are listed in the following table.

Table 1. STRESS-CORROSION CRACKING IN SENSITIVE ALLOY-ENVIRONMENT COMBINATIONS

ALLOY	SENSITIVE ENVIRONMENT
Carbon Steel	Nitrates, caustic, hydrogen sulfide
Chromium stainless steels	Halides, hydrogen sulfide
Austenitic stainless steels	Chlorides, caustic
Aluminum alloys	Sodium chloride; tropical environments; atmospheres contaminated with SO_2
Copper alloys (brass)	Ammonia; atmosphere contaminated with SO_2 or NH_3
Magnesium alloys	Fluorides, coastal climate
Nickel alloys	Caustics
Titanium alloys	Chlorinated hydrocarbons

Note* A more comprehensive listing of alloy-sensitive environment combinations in which stress-corrosion cracking has been reported has been tabulated by H. L. Logan.[3]

Atmosphere stress-corrosion tests have been conducted on aluminum alloys and steel intended for use in high speed aircraft and missiles.

Al-Cu, Al-Mg and Al-Zn-Mg-Cu alloys have been proven to be generally more susceptible to stress-corrosion cracking in seacoast atmospheres than in inland industrial or rural atmospheres. However, Al-Zn-Mg alloys with relatively low copper (7079) and no copper (7039) are just as susceptible in a less corrosive inland atmosphere as in a seacoast location.(4)

Tests results indicated that high strength aircraft steels which have yield strengths in excess of 200,000 psi, and are in the fully hardened condition, are susceptible to atmospheric stress corrosion in a severely corrosive environment such as Kure Beach, North Carolina or a moderately corrosive semi-industrial atmosphere like Monroeville, Pennsylvania. They include low-alloy steels, chromium stainless steels, and precipitation-

hardenable semi-austenitic stainless steels. In contrast, both stress-relieved and cold-worked high-strength austenitic stainless steels were found resistant to stress-corrosion in the atmosphere at Kure Beach. The semi-austenitic precipitation hardened stainless steels were also resistant to stress-corrosion in the atmosphere at Monroeville.[5]

In general, time to failure increased for the susceptible steels when the stress level was decreased from 90% to 50% of the yield strength. However, some steels exhibit about the same failure time at stress levels, of 50, 75, and 90 percent of the yield strength.[3,6]

These atmospheric tests substantiate the fact that stress-corrosion cracking does not always occur in the sensitive environments listed above for each alloy. In fact, it occurs only under certain critical combinations of factors (alloy compositions, stress level, environment and time).

CORROSION FATIGUE

Corrosion fatigue can be defined as the decline of the endurance limit of a metal caused by the action of a corrosive agent. A material in which the alternating repetition of stress is simultaneously subjected to a corrosive medium, can develop cracks which initiate and propagate far below the fatigue limit.

Because corrosion fatigue is frequently confused with the formation of cracks caused by stress corrosion, the following four differences which distinguishes between cracking by stress corrosion and by fatigue corrosion have been presented by Copson.[2]

> "First, the cyclic stresses associated with the corrosion fatigue process may lead to the formation of cracks that would not form in some environments under conditions of static stress. Second, both stress-corrosion cracks and corrosion-fatigue cracks are commonly observed to be preceded by the formation of corrosion pits from which the cracks subsequently propagate. Under cyclic-stress conditions the pits tend toward greater depth and sharpness as compared to pits under static-stress conditions which tend toward a saucer shape. Third, once the sharp pits have formed, the metal may have

> already been damaged to the extent that the cracks may continue to propagate at cyclic stresses below the normal endurance limit of the material, even if the corrosive environment be removed. Finally, the corrosion-fatigue cracks proceed predominantly in trans-crystalline fashion and in contrast to stress-corrosion, do not branch out or if they do only to a slight extent."[2]

Corrosion fatigue limits of most metals are available; however, the values of the limits are significant only when the conditions of corrosion and stressing are completely defined. The factors which have a direct influence on the corrosion fatigue limit are the atmosphere, stress, temperature, the physical properties of the metal, and its inherent corrosion resistance.[8] In general, resistance of a metal to corrosion fatigue is associated more nearly with its inherent corrosion resistance than with mechanical strength.

HYDROGEN EMBRITTLEMENT

Entrance of hydrogen atoms into the metal lattice is the cause of hydrogen embrittlement. Hydrogen is generated in metals by three known ways: by corrosion, by galvanic corrosion of a couple, and by impressed cathodic protective current. The hydrogen so generated collects in microcracks and exerts an internal pressure that may be added directly to an externally applied stress. Hydrogen may exist in pre-existing voids, also, but this hydrogen is non-damaging, and it is only the hydrogen in the stressed region that is embrittling.[3] Some material-environment combinations that foster hydrogen embrittlement cracking are given in Table 2.

Hydrogen cracking occurs more frequently in ferrous materials with a high hardness level. In these materials hydrogen has a rapid diffusion rate but limited solubility, a condition favoring hydrogen to accumulate at imperfections and dislocations. The hydrogen initiated cracks propagate by mechanical means abetted by the lower ductility and greater notch sensitivity peculiar to alloys of higher hardness levels.[7]

Table 2. STEELS SUSCEPTIBLE TO HYDROGEN EMBRITTLEMENT

Alloys	Sensitive Environments
High strength steels for aerospace applications	Hydrogen sulfide, fluorides, cyanides, industrial and marine atmospheres*
Ferric and martensitic steels (< 12% chromium)	Industrial and marine atmospheres.
Semi-austenitic precipitation hardening stainless steel (AM 350 & AM 355)	High stresses in industrial and marine atmosphere, H_2S

Note* Some of the high strength steels have failed in marine and industrial atmosphere tests after having been exposed to corrodents including chlorides, nitrates, sulfates, and phosphates. The failures are classified as stress corrosion in the literature .
It is extremely difficult, even with modern microscope equipment, to determine whether fractures in high strength steels resulted from stress-corrosion or from hydrogen embrittlement.

SECTION V

EXAMPLES OF PROBLEM AREAS

The following examples of problem areas involved failures of essential structures, aircraft and aerospace components, and communication equipment. All failures were due either to stress-corrosion cracking or corrosion fatigue, and air contaminants were a possible contributory cause in the propagation of these cracks.

A selected few failures were major catastrophes and involved staggering losses. These losses provide the basis for subsequent economic analysis.

BRIDGES

The collapse of U.S. 35 Highway Bridge (Silver Bridge) connecting Point Pleasant, West Virginia, with Kanauga, Ohio, on December 15, 1967, can perhaps be considered the most catastrophic of all structural failures in recent times. Forty-six persons perished and nine were injured when 30 of the 37 vehicles on the bridge fell with the bridge.

After three years of intensive investigation of the accident, the National Transportation Safety Board found that the cause of the bridge collapse was a cleavage fracture in the lower limb of the eye of an eyebar at a joint of the north eyebar suspension chain in the Ohio side span. The fracture resulted from the development of a critical size flaw during the 40 year life of the structure.

The final report of the Safety Board stated that a small oxide covered crack, that led to the rapid fracture, was produced by a

corrosion process. There was supporting evidence that either stress-corrosion cracking or corrosion-fatigue could have been the corrosion process.[9]

> "The mechanism of growth of the pits to cracks of critical size was first thought to have been clearly identified as a stress-corrosion action on a basis of the (National Bureau of Standards) NBS work..... Subsequent work at Battelle Memorial Institute supported the assumption of stress-corrosion, but the U.S. Steel Laboratory found evidence of transgranular fracture, indicating that corrosion-fatigue may have been involved."[9]

Battelle and NBS found that microprobe analyses indicated the presence of more than normal amounts of sulfur compounds in the crack surface. This indicated that sulfur bearing gases such as sulfur dioxide or hydrogen sulfide in the atmosphere may have penetrated into the cracks and caused them to grow by the stress-corrosion cracking process. The Battelle conclusion of their study reads in part as follows: "The crack morphology is quite typical of that normally associated with stress-corrosion cracks. No evidence was found to suggest that the crack may have been associated with corrosion fatigue. A pit near the mouth of the crack was identified as the possible origin of the crack..... Also, the highest chlorine concentrations were found at both the mouth and the tip of the crack, whereas sulfur was greatest first at the mouth of the crack.... The failure mechanism was probably sulfide stress-corrosion. Hydrogen sulfide in the atmosphere from industrial or exhaust gases could have dissolved in moisture condensed on the bridge. Hydrogen sulfide could then react with the steel and form iron sulfide in the oxide scale. Restricted areas where moisture would remain for long periods would become sulfide concentration points. The presence of sulfides, by their restriction of the hydrogen recombination reactions, would inhibit the escape of hydrogen produced during corrosion from the steel surface. Atomic hydrogen would diffuse to stress areas in the steel and cause embrittlement

and eventual failure. The role of the chloride ion probably was not to initiate the crack by itself but to reinforce the corrosion reaction thereby facilitating cracking in the presence of hydrogen sulfide."[9]

Industries located along the river and a power plant 12 miles north of the Silver Bridge could have been the sources of gaseous sulfur containing emissions. Topographical and climate conditions could have been such that at times the pollutants affected the atmosphere at the Silver Bridge site.

The Silver Bridge catastrophe is not an isolated case of this type of failure mechanism. Components of other bridges have failed by either corrosion-fatigue or stress-corrosion cracking. For example, steel cables on a bridge in Portsmouth, Ohio, failed after 12 years of service.[10] The cause of failure was traced to rain water contaminated with ammonium nitrate that had concentrated at natural crevices.

TOWERS

Researchers studied stress-corrosion cracking of insulator rocker assemblies used in guy lines that structually support high communication towers (U. S. Coast Guard). These towers are located in such remote and varied environments as Greenland, Newfoundland, Alaska, Iceland and islands in the Pacific Ocean.[11]

Initially, insulators were incorporated in the guy lines by means of eyebolts and yokes. However, two eyebolt failures occurred, and both resulted in tower destruction, The failures were attributed to cyclic torsional and bending stresses.

A rocker insulator assembly was then designed and installed to permit the eyebolt to pivot under nonaxial loads, thereby reducing the cyclic bending stresses on the eyebolt. A high strength stainless steel (AISI-420) was used for the rocker assemblies.

In less than one year's service, an inspection showed that 15 rocker assemblies on a tower in Iwo Jima had cracked. Subsequent investigation revealed that cracking was the result of stress corrosion in a humid environment containing salt air (chlorine) and a trace of hydrogen sulfide from volcanic activity.

AIRCRAFT

Stress-corrosion cracking and corrosion fatigue are major problems in both civil and military aircraft. These problems have developed along with the development and use of high strength aluminum and steel alloys to achieve greater aircraft performance. Further alloy development has reduced the magnitude of the stress-corrosion problem; however, many susceptible alloys are still being used because they have other desirable characteristics. Unfortunately, the majority of corrosion fatigue and stress-corrosion cracking failures are recorded as malfunctions or as broken or separated components and are simply replaced in the field without going through any programmed investigation. On the other hand components involved in accidents are usually investigated thoroughly by the military or National Transportation Safety Board. The purpose of these investigations is to determine the cause of the failures and that is where the investigations usually terminate. No records or statistics are kept on the environment to which the aircraft was continuously exposed.

A reasonable assumption can be made that severe atmosphere conditions can contribute to the initiation and propagation of stress-corrosion cracking in aircraft components. Naval aircraft that are exposed to salt and sulfur dioxide contaminating environments and aircraft operating close to highly industrialized areas are susceptible to stress-corrosion cracking and subsequent failure of component parts.

Three major sources of information were used in assessing the magnitude of this problem in aircraft; (1) an article [12] prepared by John S. Leak, an Air Force safety official, (2) accident reports by the National Transportation

Safety Board, and (3) the records of the Naval Safety Center. The first two sources were used to cite examples of failures and the last was used to estimate the relative magnitude of the problem and trends in related accidents within the last few years.

Air Force Experience

In 1971, John S. Leak[12] reviewed several corrosion caused accidents that Air Force Material Laboratories had investigated. Not only was the cause of material failure determined but the costs of individual accidents were estimated. These costs will be discussed in the section on economics.

Seven of the 15 reported types of failures were caused by stress-corrosion cracking.[12] Most of these failures were associated with landing gear parts made of 7079-T6 aluminum alloy. Two failures were caused by corrosion fatigue and one by hydrogen embrittlement. Thus, two-thirds of these reported types of corrosion failures were catastrophic in nature. The fraction of accidents reported is even higher because the stress-corrosion cracking examples were of numerous failures in particular types of aircraft.

Catastrophic failure of steel parts apparently was caused more often by hydrogen embrittlement and corrosion fatigue than by stress-corrosion cracking. A steel nose gear strut failed during the taxi of a small bomber.[12] The cracking of the part was caused by hydrogen embrittlement resulting from environment corrosion. Failure of steel stater vanes were attributed to corrosion fatigue.[12]

According to recent military aircraft accident records, corrosion has played an increasing role in a broad spectrum of problems and accident potential.[12] Because of the nature of some of the alloys reported to be associated with these problems, polluted industrial atmospheres are believed to be a contributing factor in these catastrophic failures.

Civil Aircraft

The Air Force is only one user of aircraft. The National Transportation

Safety Board, which investigates commercial and private plane mishaps, reports malfunctions that parallel those of the Air Force. The general pattern is the same: stress-corrosion cracking is found to be the cause of many malfunctions. Investigations do not go beyond the failure cause; what caused stress-corrosion cracking is, therefore, not determined.

Officials of the Safety Board readily admit that stress-corrosion cracking is a significant cause of aircraft component failures. The following is an example of an accident caused by stress-corrosion cracking.

> "The fatal crash of a Boeing 720B jet airliner on a training flight at Ontario, California on March 31, 1971 prompted a government warning to operators to inspect for weakened support fittings in the tail section. The National Transportation Safety Board said investigation of the crash, in which all five crew members aboard were killed, showed that a support fitting for the rudder actuator had failed. Failure of the actuator assembly on the flight results in complete loss of rudder control. An upper lug of the fitting showed evidence of stress-corrosion, and the lower lug failed because of the resulting overload imposed upon it, the Board said. The Board urged the Federal Aviation Administration to reevaluate its mandatory inspection time periods and procedures to modify them as necessary to assure safe operations. At the behest of the Safety Board, the FAA alerted operator's of 707's and 720's to inspect stablizing equipment in the tail for signs of wear. More than 1850 of the planes are in commercial service, some 700 are operated by the Air Force."[13]

Navy Experience

The Naval Safety Center collects and evaluates data on all naval aircraft accidents. These data include the general and specific classification of causes and contributing factors of accidents. For example, within the general classifications of materials failure are the more specific classifications of corrosion and fatigue. Individual accident report summaries may further pin-point the cause of corrosion-fatigue, or stress-corrosion-cracking. Complete accident reports identified by these summaries often include a description of the failed part and the particular alloy from which it was made. Thus, it is possible to estimate the number of accidents caused by stress-corrosion-cracking or corrosion fatigue of a particular alloy by examining the records of the Safety Center.

Summaries of 847 accidents for fiscal years 1966 through 1970 were examined. These accidents were identified by codes as those that corrosion or fatigue was either the cause or a contributing factor. By reading the summaries it was determined that 597 were associated with fatigue, 111 with corrosion and 139 with either corrosion-fatigue or stress-corrosion-cracking.

Stress-corrosion cracking and corrosion fatigue are difficult to identify without microscope examination of the fractured part. Also naval personnel are less familiar with these failure mechanisms than they are with fatigue. Fatigue is a transgranular failure identified by a fairly clean fracture surface marked by striations indicative of the cyclic stresses to which the part was subjected. The initiation and propagation of fatigue cracks is dependent on both number of stress cycles and stress amplitude. The rate of cracking is often sufficiently slow for cracks to be detected before parts fail. Corrosion-fatigue is similar to fatigue except that the cracks usually initiated at corrosion pits and the fracture surfaces are corroded.

In aluminum alloys stress-corrosion cracking is always an intergranular failure. The fracture surface may appear clean and bright with very little evidence of corrosion. Also stress-corrosion cracking has a long incubation period of months or years before cracks initiate and then propagate rapidly in a matter of minutes or hours. Therefore, many of the failures attributed to fatigue without subjecting the parts to microscopic examination by knowledgeable individuals, could have been caused by stress-corrosion cracking or corrosion fatigue.

The following example is typical of an accident summary that did not identify the mechanism of fracture but was very likely stress-corrosion cracking.

A TS-2A port main landing gear failed to extend for landing. The aircraft landed with the starboard main landing gear and the nose landing gear extended and the port main landing gear retracted. Both engines were feathered prior to touchdown. The nose landing gear collapsed as it passed over improperly set up arresting gear. An investigation revealed that the upper mounting bracket on the forward edge of the port outboard main landing gear door had failed and prevented full opening of that door. This in turn prevented the port main landing J-hook from

releasing the landing gear so it could extend. X-ray inspections of other aircrafts in the squadron revealed 14 of 26 main landing gear door mounting brackets were cracked and two were badly corroded.

Another example is typical of a summary that attributes the accident to stress-corrosion cracking. During a carrier landing, an F-8H bulkhead assembly failed at the main landing gear tension strut upper attachment lug fitting. An investigation revealed that failure was the result of stress-corrosion cracking.

A sample of 17 accident reports were reviewed to determine what alloys were involved in stress-corrosion cracking and corrosion fatigue failures. Only ten reports identified a particular alloy. Five of these ten reports involved failure of aluminum alloy 7079-T6. This particular alloy is known to be more susceptible to stress-corrosion cracking in industrial atmospheres than in severe salt environments along sea coasts. Because naval aircraft are subjected to both sulfur dioxide fumes from aircraft carrier stack gases and salt spray, they run a greater risk of stress-corrosion failure than if they were exposed to either contaminant separately. As the navy builds more nuclear powered aircraft carriers this risk should be reduced because the aircraft will not be subjected to sulfur dioxide fumes.

During the period from fiscal 1966 through fiscal 1970, there was no significant trend in the number of major accidents per year, the average being 492. However, there was a significant increase in the average cost per accident of 7.7 per cent a year so that the dollars lost per year tended to increase. There was a significant increase of 2.2 per cent in the percentage of major accidents for which materials failures were either the cause or contributing factor.

The number of corrosion-fatigue and stress-corrosion failures for fiscal years 1966 through 1970 shows a significantly increasing trend. A linear least squares fit of the data suggests that the rate of increase in the number of failures is about five per year.

Forged aluminum aircraft parts are mass produced to reduce costs and give uniform quality. Therefore, when a particular forging on an aircraft fails by corrosion fatigue or stress-corrosion cracking it is reasonable to expect other failures of the same part on similar aircraft. This behavior is exemplified by the fact that in 1969 there was a rash of accidents in S-2 type aircraft caused by corrosion-fatigue wheel failures. This type of accident usually leads to examinations of similar parts of similar aircraft. These checks normally find many previously undetected cracks. The parts are then replaced or repaired and directives issued to specifically check such parts for cracks when regular inspections are made. This procedure reduces the number of subsequent accidents but increases the preventive maintenance workload. It should be possible to prevent the first accident resulting from a particular type part corrosion-fatigue or stress-corrosion failure by detecting such cracks on regular inspections and issuing directives to watch for cracks in specific parts.

ELECTRICAL EQUIPMENT

In 1959 telephone equipment in the Los Angeles area began to show considerable breakage. High levels of airborne nitrates were found to be the cause of stress-corrosion cracking of nickel-brass telephone relay contact. A field survey was made of the nitrate deposition on telephone equipment in central offices throughout California.

The survey showed that the amount of nitrate accumulation correlated with the amount of spring breakage and corresponded to the general pattern of smog and air pollution existing in California. Failure of the relay springs was due to stress-corrosion cracking of the nickel-brass wire under the influence of an applied positive potential, high surface nitrate concentrations, and relative humidity above 50 percent. The survey results were used to determine where counter-measures, such as humidity control and high efficiency incoming air filtration, were most needed. Also, on new relay parts a cupro-nickel alloy, which does not stress crack in this manner was substituted for the nickel-brass.

Considerable time and money was spent in the investigation of the cause of failure, in the research of a substitute alloy, and in the replacement of parts.

A similar investigation pertaining to atmospheric exposure effects on the fatigue strength of stainless steel and nickel silver wire springs for relays took place in Japan (1968) for the Nippon Telegraph and Telephone Public Corporation.[15] The worst corrosion behavior was observed in nickel silver where stress-corrosion cracking appeared after one month; pitting occurred in stainless steel and nickel coated stainless steel. X-ray analysis of the corrosion products that sulfur and chlorine were present in the stress-corrosion cracks in the nickel-silver and in the pitted areas of the stainless steel.

SECTION IV

ECONOMIC IMPACT OF AIR POLLUTION CAUSED CATASTROPHIC FAILURE OF METALS

The costs associated with pollution accelerated catastrophic failures, at best, only can be very rough estimates yet these estimated are needed to assess the magnitude of the problem so that it can be placed in proper perspective.

Two major costs are involved: (1) the costs of failures, and (2) the costs of prevention of failures. The former can be estimated from data associated with the examples presented in the previous section. The latter is more difficult to assess.

COST OF FAILURES

The cost of catastrophic failure will be based on those examples given in the previous section for which cost data were available or could be estimated.

Bridges

The "Silver Bridge" disaster is an extreme example of what can happen when this type of materials failure occurs. The overall estimated costs of the catastrophe are staggering. They are based on correspondence with:

Mr. Logan L. Ratliff

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It is estimated that legal suits will eventually run up to about $70 million. The cost of the investigation, which took three years to complete, is conservatively estimated at $70 million. This included the removal of wrecked structure, the maintenance of vital traffic (initiation of ferry service was essential) and the overall investigation.

The Corps of Engineers, U. S. Army, completed the massive recovery of the parts of the bridge from the Ohio River and conducted additional searches for missing parts. The Administrator of the Federal Highway Administration gave continuing support and approval for expenditure of extensive research funds and provided professional assistance to the Safety Board through representatives from the Bureau of Public Roads and the Bureau of Motor Carrier Safety. Representatives to the investigation included the States of West Virginia and Ohio, four separate consulting engineering firms and the American Bridge Division of the U. S. Steel Corp. Extensive Laboratory work was assigned to the National Bureau of Standards, Battelle Memorial Institute, the U. S. Steel Applied Research Laboratory and the Structures Laboratory of the Federal Highway Administration.

Indirect costs (economic cost to the surrounding area) are difficult to assess and evaluate, but estimates from local sources place the cost at $35 million. This would include losses due to the rerouting of traffic, especially trucking, and business losses on each side of the river bank. For example, a milk processing plant was forced to close due to the unfavorable economic circumstances resulting from the catastrophe.

Reconstruction costs including the replacement of the structure ($8.5 million), the Ohio approaches ($35 million) and the W. Virginia approaches ($5.5 million) are not totalled into the cost of the catastrophe, because for other reasons, the bridge should have been replaced prior to the failure.

Summarizing the costs of the catastrophe, that is, the legal suits and the direct and indirect costs, the total estimate comes to $175 million. Lacking additional data this figure can be used to extrapolate costs for other possible bridge failures.

Because this is a single value obtained for a forty-year bridge life, we may assume that such a major accident probably will not occur more than once in forty years although less severe bridge failures are expected to occur much more often. The total costs for the less severe failures should exceed the cost of a single major catastrophe. Thus, we can roughly assume that bridge failures caused by catastrophic cracking of materials may cost the nation approximately one-half billion dollars over a forty year period or approximately $12 million a year.

Air Pollution contributes only a fraction to the catastrophic failure so that only a fraction of the $12 million per year can be a cost of air pollution. Because of the lack of information on the acceleration of failure by air pollution, $4 million per year arbritrary is assigned as air pollution cost. Other material and environmental factors are the major contributors to such failures.

Towers

Communication towers (radio, television, navigation aids) are usually located in rural areas where air pollution is not a problem. Although failures have occurred and the costs are significant to those involved, the annualized cost to the nation as a result of air pollution's contribution to such failures is considered negligible relative to other air pollution caused failures.

Aircraft

The best accident cost figures for failure of aircraft parts are based on Naval Safety Center data. The damage cost of major naval aircraft accidents averaged $448 million per year for fiscal years through 1966 through 1970. Although there were variations in costs each year there was no significant trend over the five year period. There was a significant trend in the percentage of major accidents for which materials failures were either the cause or a contributing factor.

This trend represents approximately an increase of 2 per cent a year. Thus, it appears that during this period, improvements in pilot safety programs were offset by deteriorating aircraft conditions. An increasing average age of aircraft increases the probability that delayed catastrophic failure (that is difficult or impossible to detect during normal inspections) is the operating mechanism. An extrapolation to fiscal 1974 indicates that materials failure will be involved in approximately 70 per cent of the major naval aircraft accidents for an estimated cost of around $315 million.

A trend in the percentage of minor accidents associated with materials failures is even more significant (an increase of over 3 per cent per year). There was also a significant increase in the cost of minor accidents over the five year period. An extrapolation of the combination of these trends gives an estimated loss of $15 million in fiscal 1974 associated with materials failures. The total estimate for major and minor accidents is $330 million per year caused by material failures.

Based on examination of accident summaries, approximately 16% of material failures are associated with stress-corrosion cracking or corrosion fatigue. Thus, in fiscal 1974 it is estimated that corrosion-fatigue and stress-corrosion cracking will contribute approximately $53 million in losses due to naval aircraft accidents.

Air Pollution contributes only a fraction to these losses: Sea salt is a major contributing factor. Lifka and Sprowls [16] have determined times to failure of aluminum alloys stressed at different levels of stress in industrial and sea coast environments. These data may be used to estimate the fraction air pollution contributes to stress-corrosion failure of aluminum alloys. Failures of 7079-T6 aluminum alloy test specimens occurred sooner at industrial sites in New Kensington, Pa., and Cleveland, Ohio, than at seacoast sites in Pt. Judith, R. I.; and Pt. Comfort, Texas. The investigators did not measure the pollutant levels but they should be relatively high at the industrial sites and low at the sea coast sites. The reverse should be true for chloride concentrations in the air.

Analysis of these data indicates that the average life at the industrial sites is less than half of what it is at sea coast sites. Thus, over a long period of time industrial pollutants should contribute twice as much to failures than does the salt of a sea coast environment. Naval aircraft are subjected to both insults, not necessarily in equal amounts. Based on these considerations, an estimate of $25 million annual accident loss to naval aircraft associated with an air pollution accelerated catastrophic materials failures appears to be reasonable.

The Air Force study[12] reported a cost of 20.5 million dollars associated with the selected stress-corrosion cracking and corrosion-fatigue caused accidents. These figures represent not more than a dozen accidents for a three year period. The Navy data indicate more than twice as many such accidents a year. It is believed that the total for the Air Force accident losses of $25 million a year associated with air pollution accelerated catastrophic failure of parts is a reasonable estimate.

Civil aircraft are not subjected to the same environments and fewer failures are expected than for the military aircraft, although catastrophic failures do occur. Because of the lack of documented evidence an arbitrary loss of $5 million a year is estimated.

The total annual loss due to aircraft accidents caused by air pollution accelerated catastrophic failure of metals is estimated to be $55 million.

Electrical Equipment

The reported air pollution caused failures of electrical relay springs[14] is not an isolated case. Similar failures have occurred around the country.[17] Although there is some cost associated directly with the failure, the major cost is associated with the research necessary to determine the cause and find a fix. One million dollars a year is a

conservative estimate of the total amount of research involved in this particular type of problem.

COST OF PREVENTION OF FAILURES

Research, alloy development, design, inspection and maintenance are means by which catastrophic failures of metal parts are prevented. The cost of research, development and design is recouped by companies in the sale price of new, improved products. This increased cost may not be necessary under cleaner environmental conditions. That is, the old product may perform satisfactorily with air pollution absent. The user of a product pays for inspections and maintenance to insure satisfactory service. Not as much maintenance may be necessary without air pollution.

Research, Development and Design

The cost of research, development and design is difficult to assess but a rough estimate can be obtained by estimating the number of people working in the field. A significant conference on "Fundamental Aspects of Stress-Corrosion Cracking"[18] was held in 1967. Attendance was by invitation and 126 scientists were there. Assuming each had his own research project, and was working full time on the problem, the annual cost to do this research is approximately $5 million. Only about 35 per cent of the papers delt with mechanisms associated with atmospheric failures. Also air pollution could be associated with approximately half of those mechanisms. Thus, one million dollars in research by these individuals could be attributed to air pollution. Because many more people are involved in such research and development, $10 million is assumed to be associated with air pollution.

Inspection and Maintenance

Based on figures provided by the Naval Air Atlantic Fleet, it is roughly estimated that the Navy spends annually $16 million for corrosion correction and control. This figure includes aircraft down time, parts and labor. Examination of accident summaries indicate that 56 per cent of

corrosion associated accidents are caused by stress-corrosion cracking and corrosion fatigue. The same percentage of preventive costs should be applicable. Thus approximately $9 million a year is estimated as spent by the Navy for maintenance to prevent catastrophic failure of parts by stress-corrosion cracking and corrosion fatigue. Air Pollution's contribution to this loss is estimated at $5 million.

These rough estimates based on Navy data indicate that the loss due to air pollution induced catastrophic failure is five times greater than the cost of maintenance to prevent such failures. Applying this ratio to other accident loss values, the remaining costs for preventive maintenance can be estimated. Thus, such annual costs should be approximately, $1 million for bridges, $5 million for Air Force aircraft, $1 million for civil aircraft, as well as $5 million for Navy aircraft, for a total of $12 million.

SUMMARY OF LOSSES

All of these estimates are expressed to the nearest million dollars. The assumptions made in calculating these estimates only warrant carrying two significant figures. These losses are summarized in Table 3.

Table 3. ESTIMATED ANNUAL ECONOMIC LOSSES CAUSED BY AIR POLLUTION ACCELERATED CATASTROPHIC FAILURES OF METAL PARTS

Structure	Loss - Millions of Dollars			
	Accidents	Prevention		
		Research	Maintenance	Total (Less research)
Bridges	4		1	5
Aircraft				
Air Force	25		5	30
Civil	5	10	1	6
Navy	25		5	30
Electrical Components	1			1
Total	60	10	12	82*

*Includes Research

The magnitude of the error in the $82 million estimated value is more difficult to obtain than the value itself. Many assumptions have necessarily been made because of lack of documented evidence. It is possible that other major structural systems are subject to similar catastrophic failures. Thus, the actual value for the economic loss could be higher or lower, and as an "educated guess" probably lies between $50 million and $100 million.

Six similar studies have been completed on (1) metals, (2) paints, (3) textiles, (4) Elastomers, (5) electrical contacts and (6) electronic components. The annual loss estimates from these studies ranged from $15 million for electronic components to $1,450 million for metals. The $82 million figure from this study ranks between $64 million for electrical contacts and $500 million for elastomers or fifth in a series of seven.

SECTION VII

DISCUSSION

In this report, relatively few cases of catastrophic failure of metals have been used as examples that can be associated with air pollution. Stress-corrosion cracking, corrosion fatigue, and hydrogen embrittlement are such insidious mechanisms of metal structure failure that many times they are overlooked as the cause. Failure of parts in consumer products are seldom investigated unless litigation is involved. Therefore, the economic magnitude of this problem could be much greater than it appears from documented evidence.

The $82 million annual loss estimated in this study is a minor but significant contribution to total economic losses associated with existing levels of air pollution. More important is the fact that the types of catastrophic failures that constitute this loss sometimes result in human injury and loss of life. This factor places this problem as much in the area of human health and safety as in the area of welfare. As such, it should be considered in the establishment of future primary standards.

Unfortunately, there has been no research to determine relationships between air pollution levels and the occurance of catastrophic failures of metals. Such information is vital to setting air quality standards.

Because stress-corrosion cracking and corrosion fatigue are delayed failure mechanisms, research on these effects is time consuming and is accomplished by long term, low level projects lasting several years. Thus, from the time work is initiated to the time information is available for setting standards could be between five and ten years.

SECTION VIII

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